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Discovery, identification, and study of variability in gamma-ray point sources

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Abstract. We present preliminary results of a statistical analysis obtained with a sample of blazars observed at the Perugia Astronomical Observatory since 1992. We briefly show how these statistical results can be useful to discriminate faint variable sources against the background noise. This technique, together with the more traditional ones, may be used to discover and identify high-energy point sources.

1. Statistical analysis of variability

Many of the expected high-energy sources are variable, like blazars which emit signals that often appear to vary chaotically with time.

Does such signal result from the superposition of many random events (randomly generated shocks in outflowing gas; randomly appearing reconnections of magnetic field lines; etc.)? Or they are governed by some global physical mechanism described by non-linear differential equations, which shows deterministic chaos (coherent variability of clouds of electrons; instability of a shock at the base of the jet forming region; etc.)? Finally, is it possible to find same kind of periodicity, at least in particular intervals of time (hot spots in the rotating accretion disk; helicoidal movements of the jet; etc.)?

For a reasonable answer to these questions, we can use - for example - one or more of the following statistical analysis:

- *correlation, autocorrelation, power spectrum estimation, with FFT:* future high energy missions working in scanning mode (like GLAST) probably will provide data well sampled at evenly spaced intervals, that can be processed with the Fourier Transforms;
- *correlation, autocorrelation, power spectrum estimation, with the Lomb-Scargle periodogram*, (Lomb 1976, Scargle 1982) for irregularly or incompletely sampled data;
- *correlation and autocorrelation with the Discrete Correlation Function (DCF)* described by Edelson & Krolik (1988), useful for unevenly spaced data;
- *first order Structure Function (SF)*, because there is a simple correspondence between power laws in the frequency space Fourier analysis, and the SF analysis in the time domain (see, e.g., Hufnagel & Bregman (1992);

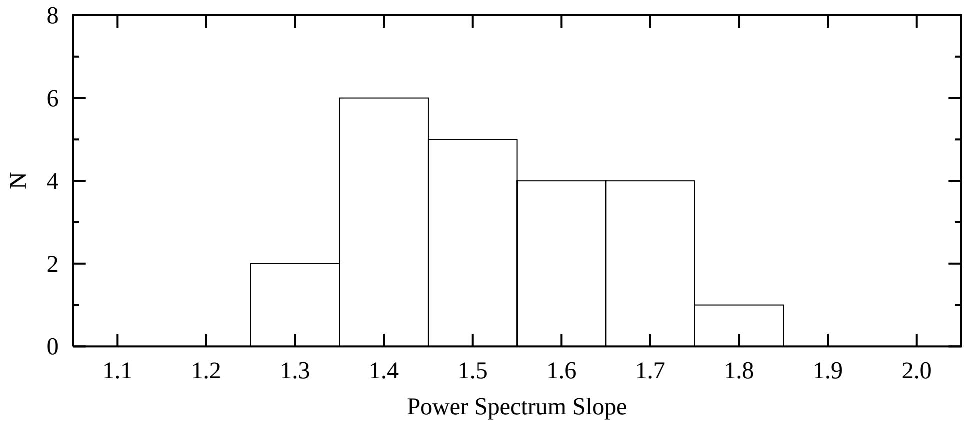

Figure 1. Distribution of the PSD slopes (α). The estimates are done using the SF and DACF, with a sample of blazars observed at the Perugia Astronomical Observatory.

- *detrended fluctuation analysis*, that permits the detection of intrinsic self-similarity embedded in a seemingly nonstationary time series (see, e.g., Peng et al. 1995);
- *the wavelet methods*, that together with principal component analysis and filtering can be used to extract the "deterministic" components from the time-series (see, e.g., Liszka & Holmström 1999);
- *a search for chaotic behavior*: the most popular measure of an attractor's dimension is the correlation dimension, first defined by Grassberger & Procaccia (1983).

We are using these and other less-known statistical techniques with the BVR$_c$I$_c$ database of the Automatic Imaging Telescope at the Perugia astronomical Observatory (Tosti et al. 1996). Preliminary results have been already described in Fiorucci et al. (1999, 2000), and suggest that the observed variability is truly stochastic and is not caused by deterministic chaos. Moreover, many of these statistical descriptors lead to the provisional conclusion that variability of blazars is self-similar on time-scales from a few days up to some years, and it is characterized by power-law power spectrum $PSD(f) \propto f^{-\alpha}$, where the spectral slope α is in the range $1.3 - 1.8$, with an average value $\alpha = 1.51$ (see Fig.1). To provide a frame of reference, it is convenient to consider two well known cases: white noise has $\alpha = 0$ and Brownian motion has $\alpha = 2$.

The point is that this kind of variability is observed in all the AGN class (see, e.g, the results of Webb & Malkan 2000), and it does not seem to be exclusive of the optical wavelengths: *AGNs seem to be characterised by variability similar to pink (or red) noise in a large range of frequencies.* The X-ray light curves have power spectra with slopes in the range 1 to 2, (see, e.g., Lawrance & Papadakis 1993). Radio light curves have power spectra with slopes around 2 in time-scales from days up to some years (see, e.g., Hufnagel & Bregman 1992, Lainela & Valtaoja 1993). Moreover, we expect to see a similar behavior at higher energies

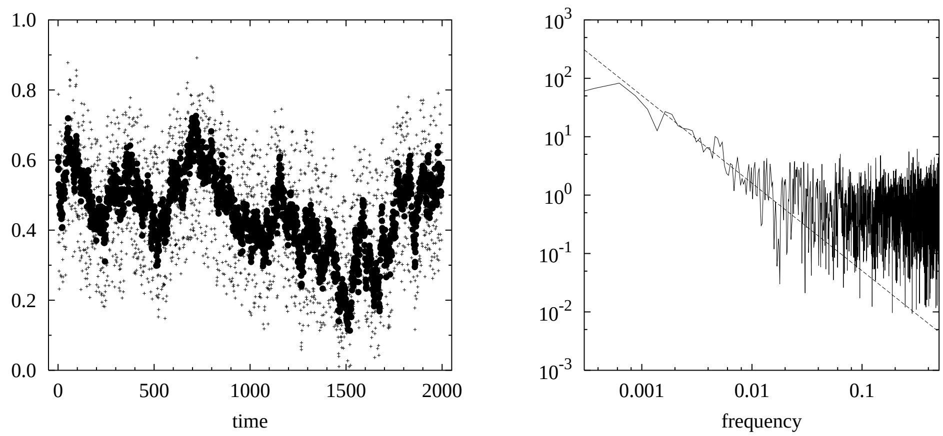

Figure 2. The left panel shows the simulated "identification" of a variable source (filled circles) from a noisy time-series (crosses). The signal is corrected with the optimal (Wiener) filter, assuming that the PSD has a $f^{-1.5}$ behaviour added to a white noise tail (right panel). Arbitrary units are used.

too, because in the majority of theoretical models for AGNs there is a strictly correlation between γ-ray photons and low-frequency ones. If this scenario will be confirmed also with future observations, then the problem will be to identify the real time-scales and to understand the physical reasons behind this kind of variability. For the moment, we can try to use this observational evidence to improve our techniques in the research of this class of objects during all-sky surveys.

2. Application to the next high-energy missions

EGRET detected 271 point sources (Hartman et al. 1999), but only 101 of them were identified and, of them, 93 are AGNs. The next generation gamma-ray instruments probably will increase this number to many thousands, but it is often crucial to discriminate faint variable sources against the background noise.

For this kind of problem it is generally used the likelihood analysis (Mattox et al., 1996), that take into account the spatial and energetic distributions of the data. Together with the more traditional techniques developed for a correct discovery and identification of high-energy point sources, we believe that it would be useful to use also the variability tools, for a correct inclusion of the time domain yet during the first elaboration. In fact many astronomical sources (as AGNs, black hole X-ray binary systems, and also Gamma Ray Bursts) show variability characterised as *red-noise* in a large scale of frequencies.

For example, Fig.2 shows the application of a traditional technique (the Wiener filter, see Press et al. 1992) for the "identification" of a simulated variable source with the assumption that the power spectrum has a $f^{-\alpha}$ behavior added to a white noise tail. With the original simulated signal it is quite difficult to verify the presence of a variable source respect to the background noise (assumed as white noise), because the fluctuation is within the limit of three standard deviations. The filtered signal puts in evidence the presence of a "possible" point source, characterized by *red-noise* variability.

3. Final remarks

All the above mentioned statistical methods can be very useful for a rough estimation of the physical phenomena, but unfortunately they are not conclusive because the results are always strongly affected by many external factors. For example, the Structure Function seems to show a strong dependence from the more intense flares, while the Discrete Correlation Function and the Detrended Fluctuation Analysis are influenced by the large gaps in the light curves.

Moreover, it is not clear if the *red-noise* behavior is a typical feature of AGNs at the gamma-rays frequencies too, and what is the statistical behavior of the background noise for the next generation high-energy detectors.

For all this reasons we are developing a Monte Carlo technique to test all the more useful statistical descriptors, and to produce a reliable quantification of the results so obtained. In the same time, we intend to develop a neural network technique that can be used to analyse the time series, to find the embedding dimension of the characteristic attractor, and to perform well the frequency extraction in unevenly sampled signals. Finally, we are developing a light simulator for the Large Area Telescope (LAT) onboard of the GLAST satellite, with the aim to test the possible use of variability tools to discover and identify γ-rays point sources.

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